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Institute for Basic Standards
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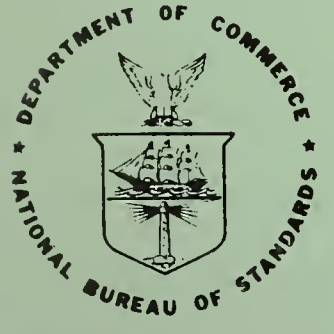

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AN IMPROVED PHOTOGRAPHIC EDGE-ARTIFACT

By

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ABSTRACT

The history of edge-objects for use in optical and photographic testing is briefly reviewed and culminates in a short summary of the technique developed at NBS in 1965 for producing photographic edges by x-ray exposures on high resolution photographic plates with a tantalum strip to generate the discontinuity. The report then covers the development of an improved method for producing these edge-artifacts. It is shown that with x-ray exposure, the relation of density to exposure is linear up to densities of approximately 2.0. This linear relation is then exploited to produce two kinds of edge-artifacts. Both artifacts contain ten (10) values of density and three edge-discontinuities. The edges on one artifact have the same value of contrast, with different mean densities, while the edges on the other have different values of contrast. The use of each type is discussed. Techniques for determining exposures, for determining the transmittances of the aluminum step tablets used to modulate x-ray exposure and for determining the linear relation between density and exposure are presented in mathematical detail and exemplified in subsequent illustrative experiments. Some inherent limitations of the method are discussed. It is concluded that there is sufficient flexibility to the process and procedures to provide sharp edges, in a wide range of contrasts, on demand.

INTRODUCTION

The use of an edge-discontinuity in the determination of acutance for photographic materials[1] and in the evaluation of optical systems through edge-gradient analysis[2] has been well-explored and documented. Implicit in these techniques is the perfect quality of the edges used; if perfection has not been specified or implied, their quality has always been assumed to be significantly better than the system they are to test. Thus, a premium has been placed on the production and calibration of near-perfect edges. The problems associated with edges can be categorized under "usage" and "fabrication", although they are not totally unrelated.

Fabricating a usable edge has always been difficult. Perrin describes the difficulty in making good edges[3] and the literature is replete with references to such problems. Since the edges must be better in quality than the systems they must test, optical imaging of an edge-discontinuity to produce an exposure on a high resolution emulsion contains a number of inherent limitations that preclude such a fabricating technique. Clear and opaque edges are not useful for testing films or optical systems. With films, if adjacency effects are present in processing, it is better to have maximum and minimum densities on the straight-line portion of the characteristic curve for quantitative analysis; transmittances of 1 and 0 (clear and opaque, respectively) cannot be usefully accommodated on the majority of photographic materials since the useful dynamic range is not large enough. In optical system testing, it is best to delimit the input illuminance since most systems do not have a dynamic range capable of handling that provided by a clear and opaque edge-artifact.

In use, in the determination of the acutance of photographic materials, the edge must be held close to the photographic material so that diffraction effects are minimized. On the other hand, if excessive pressure is used to hold the edge against the material, the material itself may be damaged or compressed, leading to a thickness variation, sometimes a cut, that adversely affect results. These same considerations apply to the fabrication of an edge by photographic contact-printing.

In an optical system the edge is imaged, and it is important that the edge-transmittance attenuate the illumination solely by absorption; i.e., be non-reflecting. Reflective edges tend to introduce additional non-image forming light (usually flare or a modification of the flare already in the system), which by virtue of its one-sidedness results in an apparent system impulse response that is asymmetric. Further, the light introduced by the reflection, although small, limits the high-density side of the image to values generally less than 2.0. These effects are present even with purely absorptive materials, and the reflections exacerbate the problem.

Two Approaches to Fabrication:

There have been various approaches to the fabrication of edges. Eyer[4] employed edges in contact-printing that were made by carefully folding a piece of one-mil aluminum foil. The folded edge was then rolled under pressure, blackened (the reference does not specify the means) and then mounted on a glass plate. In his microdensitometer, the density of the scanned edge dropped from "...an effectively infinite value to zero in less than three microns."[4] The only microdensitometer parameter cited in

his paper is the sampling aperture, which was held constant at 1 x 300 micrometers. The instrument he reported using is generally operated with matched numerical apertures and nearly always employs image-scanning[5]. If the microdensitometer performance was at all linear, the edge was indeed of exceptional quality.

Razor blades are a traditional tool in preliminary experiments calling for edges, but are inadequate when useful accuracy and precision in measurement are required. Nicks and other inhomogeneities along the edge, its opacity and the unwanted reflections from the shiny surfaces quickly rule out this type of artifact. In a variation of the razor blade, use of a reflective edge was described in 1964[6]. Here, a silvered surface of glass was scored with a diamond tool and all the silver to one side of that line subsequently scraped off. Not surprisingly, unwanted reflections held useful instrument measurements to densities below 2.0. When used as a master to produce photographic edges (through contact-printing on Reprolith film*) however, these reflections did not affect exposure quality, and the resultant edges proved to be useful at higher densities.

These kinds of experiences, together with the preceding discussions, lead to the specification of ideal edges for optical and photographic testing. These edges should have the following properties:

1) A near-perfect discontinuity for the edge, blemish-free, uniform density on either side of the edge;

2) The artifact should be free of marks, cuts, compressed or swollen areas and, if made photographically, should be free of adjacency effects;

3) Density should be manifested by absorption; reflective edges are to be avoided;

4) To reduce the effects of system flare light, and to exhibit non-linear effects (if they occur), densities should not exceed 3.0 nor be less than 0.30, approximately; transmittances of 0 and 1 are to be avoided.

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*Certain commercial equipment and materials are identified in this report primarily to specify the experimental procedure adquately. In no case does such identification imply recommendation or endoresement by NBS, nor does it imply that those identified are necessarily the best available for the purpose. Further, the equipment or materials may not be identical to those products currently on the market that bear nominally similar designations of type.

The Initial NBS Effort:

To realize these objectives and to provide a source for physical edge standards in the optical and photographic community, McCamy and Berkovitz, at the National Bureau of Standards, developed a technique for making photographic edges of extremely high sharpness that were non-reflective. The work was reported at the 1965 annual conference of the SPSE[7]. Briefly, the method employed x-ray exposure of Kodak high resolution plates. The discontinuity in exposure was obtained by inserting a 10-mil thick strip of tantalum into the exposing radiation, in contact with the photographic material. The edge of this strip had been optically smoothed and polished and was clean, without nicks. Tantalum is capable of precision machining because of its hard, compact structure, yet thin strips are not brittle. It has a high attenuation for x-rays (paraticularly in the 20 to 50 kV range) because of its relatively high atomic number. The subsequent chemical processing of the exposed emulsion was devised to eliminate or minimize adjacency effects. Those NBS edges have served the optical and photographic community well, and have been available from NBS since 1965.

The Current NBS Effort:

In 1972, with the publication of papers on microdensitometer linearity[8,9,10] interest in using edges for microdensitometer performance evaluation received a new stimulus. By 1974, the supply of edges at NBS had been exhausted, and it was felt appropriate to review the entire process, so that format changes could be considered and the tantalum strips re-worked.

By then, the original process had been modified slightly, to provide minimum densities that were above the toe of the characterisitic curve (by pre-fogging the material in visible light prior to x-ray exposure). Step tablets of the same material with identical processing routinely accompanied each edge. Thus, each edge artifact consisted of two glass plates, 2.5 x 7.6 cm, with the one having an edge discontinuity running the full 7.6 cm length. Edge contrasts varied from high ($\Delta D = 3.0$) to low ($\Delta D = 0.30$), and were neither standardized nor reproducible.

After review, it was decided that the edges and step tablets could be combined on the same physical standard and the two basic artifacts would be developed and standardized:

1) ten-step tablet, incorporating three edges of different contrast;

2) ten-step tablet, incorporating three edges of identical contrast but of different average density.

The first of these would be useful for normal system testing, at low, medium or high contrast. The second would be useful for exploring the photometric response of systems, holding the input contrast constant but varying the mean illuminance. These artifacts are extremely useful for evaluating microdensitometer performance. The short working distances associated with the high numerical aperture optics commonly employed in these instruments preclude the use of artifacts on glass plates. Thus, it was also decided to make the artifacts available on film.

Scanning electron micrographs of the tantalum edges showed the need for rework. After optical polishing, it was found that the edge was unsuitable and a new approach was taken. The tantalum strip was embedded in an epoxy and given a metallographic polish; the final polishing grit particles were nominally 0.05-μm in diameter. Scanning electron micrographs of the edge of the tantalum strip showed a definite improvement in quality over those that were optically polished.

It was felt that a detailed investigation of the basic process was warranted, in the expectation that a mathematical framework could be developed for specification of exposures, contrasts and densities. This would facilitate production of two "stock" artifacts and permit fabrication of customer-specified edge-density differences, if demanded. The investigation of the theoretical aspects of the process is reported in the following section. The results of experiment are reported in a subsequent section.

THEORY

A large amount of research has been reported on the exposure of photographic materials to x-rays. These have been so well summarized in reference 11 that their individual citition need not be given here. Among the many useful facts reported are the following:

1) The image with x-ray exposure is stable at room temperature and moderate humidity; latent image-fading increases with increased temperature and humidity.

2) There is no reciprocity law failure nor intermittency efferts with x-ray exposures.

3) Density is a linear function of exposure with x-rays, for densities up to at least 1.0, and often as high as 2.5.

While these are all significant for the present program, the latter has the most immediate impact. It has been found possible to extend the normal linearity with x-ray exposures by using high resolution emulsion exposed and processed for the toe of the normal characteristic curve. Furthermore, in contrast to what we intuitively expect from these materials processed to low densities, the image densities are close to neutral.

Figure 1 contains a plot of density versus exposure for high resolution emulsion (film and plate) exposed and processed under the conditions to be described in the experimental section. It is clear that the lower portions of each of the curves can be represented by an equation of the form

$$D = A\,E + C, \qquad (1)$$

where

D = Density;

E = Exposure;

C = Base-plus-fog density;

A = Constant: characteristic of light intensity, film speed, chemical processing, etc.

To modulate exposure, we can either vary the intensity of the source or attenuate a constant illuminance by a step tablet. The latter has a much greater range of variation and is inherently more stable. For a given exposure time and source intensity, the density of the resultant exposure and processing depends on the transmittance of the corresponding portion of the tablet. With x-rays it is convenient to use a step tablet consisting of layers of aluminum foil. Thus, for a transmittance due to k layers of aluminum foil, the linear relation of Eq. (1) becomes

$$D(k) = A\,T(k)\,t + C, \qquad (2)$$

where

$T(k)$ = transmittance for k layers of foil,

t = exposure time,

The other terms retain their previous meaning.

In the section on experiment, these constants will be determined and the range of validity of the equation clearly established. Until then, we postulate the uniform applicability of Eq. (2) and next consider the exposure of the photographic materials for edges.

Photographic Edges:

There are two basic types of edge-artifacts we consider. Both contain three edges and ten patches of uniform density. One has edges of different contrast (VCE) while the other has edges of constant contrast (CCE). The uses of each have already been discussed. We will consider the techniques

of exposing these two artifacts, using the tantalum strip previously introduced to achieve the edge-discontinuity. We specify contrast across edges as density difference, since this is the most useful measure, and denote it by ΔD.

Variable-Contrast Edges

A tantalum strip is laid along a piece of film, approximately dividing the width of the film in half. Over this is placed a five-step tablet of aluminum foil layers. All three are placed in the beam of x-radiation and exposed for a time, t_1. The exposure on that portion of the film covered by the tantalum is zero, while that portion not covered by the tantalum can be described by

$$ {}^{1}E(k_i) = T(k_i)\, t_1, \tag{3} $$

where the superscript denotes the first exposure series. The exposure history at this point is sketched in Figure 2a.

The x-radiation is now stopped, the tantalum strip is removed, and the film and accompanying step tablet are exposed for a time, t_2. The second exposure adds another exposure to the format and can be described by

$$ {}^{2}E(k_i) = T(k_i)\, t_2. \tag{4} $$

The exposures of Eqs. (3) and (4) add; the summary is sketched in Figure 2b.

The density differences $\Delta D(k)$ produced by these exposures and the linear characteristic curve of Eq. (2) are given by

$$ \begin{aligned} \Delta D(k) &= A\left\{T(k)\, t_1 + T(k)\, t_2\right\} + C - \left\{A\, T(k)\, t_2 + C\right\} \\ &= A\, T(k)\, t_1. \end{aligned} \tag{5} $$

This shows that the contrast of each edge is determined by the transmittance of the corresponding step on the tablet and is proportional to the first exposure time.

To produce a given ΔD, we must have information about the sensitometry, since this enables us to determine $T(k)$. In Appendix A the system sensitometry is discussed in detail, and is based on knowledge of the

transmittance factors for the aluminum step table, T(k). There it is shown that

$$T(k) = \exp\left[-(a_1 + a_2)k + a_2 k^2\right], \qquad (6)$$

where

$$k = \text{number of layers of aluminum foil,}$$

and the constants a_1 and a_2 are determined by experiment and subsequent analysis. In that same analysis, the constant A, necessary for the linear characteristic curve, will also have been determined.

Let us specify three $\Delta D(k)$'s that are to be produced on the artifact, $\Delta D(k)_1$, $\Delta D(k)_2$ and $\Delta D(k)_3$, and order them so that $\Delta D(k)_1$ is least and $\Delta D(k)_3$ is the largest. From Eq. (5), with knowledge of constant A, we can write

$$T(k)_i t_1 = \Delta D(k)_i / A. \qquad (7)$$

It is clear that the largest value of $\Delta D(k)_i/A$ can be attributed to the largest $\Delta D(k)_i$, since it is in the numerator. Further, since we want at least one step on the tablet-artifact higher than any density related to the three edges, we must choose k greater than 0; k = 1 is probably the most effective in terms of exposure. Then if we make this choice, we have

$$t_1 = \Delta D(k)_3 / A T(1). \qquad (8)$$

With this value of t_1 established, we can now solve for $T(k)_i$ for the other two steps, through

$$T(k)_i = \Delta D(k)_i / A\, t_1. \qquad (9)$$

Since the analysis that produced the value of A also produced a listing of k versus T(k) (see, for instance, Table I), the value of k closest to the value of $T(k)_i$ given by Eq. (9) is taken for the given $\Delta D(k)_i$. Thus, the correct values of k_1, k_2 and k_3, as well as the first exposure time, t_1, are determined quickly and with a reasonable accuracy. Clearly, it is not possible to produce an edge contrast precisely through choice of k, since T(k) is not a continuous function and only seven aluminum layers

are ordinarily used. However, a choice of t_1 will allow some selection for at least one of the three edge contrasts.

An alternative method for finding the k_i's results from combining Eqs. (5) and (6), taking natural logarithms of both sides of the equation and solving by quadratic formula for k. The resulting relation is

$$\text{int}(k_i) = a_3/2 \pm (1/2) \sqrt{a_3^2 - (4/a_2)\log_e \left\{ (At_1)/\Delta D(k)_i \right\}} , \quad (10)$$

where $a_3 = (a_1 + a_2)/a_2$,

and $\text{int}(k_1)$ is interpreted as the nearest integer value of k.

As with the first method, determination of k must start with the highest value of the required $\Delta D(k)$. However, no convenient provision is made for establishing the first exposure time, t_1, and a great deal of trial-and-error is necessary before the constants are determined. The first technique is clearly preferable, but both are acceptable.

Since the tablet-artifact will have five regions of exposure, the middle three of which have been specified by k_1, k_2 and k_3, the remaining two specifications are optional. If k_1 has been chosen to be 1, the lower value will necessarily be k = 0, since there is nothing beyond that. The upper value can be chosen to provide densities that would be useful for the tablet.

To keep the artifact densities on the linear portion of the density-exposure curve (and thus achieve predictable results), the upper density limit must not be exceeded. Since the $\Delta D(k)$ are related to $T(k)$ and t_1, we must determine the first-exposure time first. Then, since ${}^1E(k_i) + {}^2E(k_i)$ will be the larger exposure,

$$D(k)_{max} = A \left[{}^1E(k) + {}^2E(k) \right]_{max} + C$$

$$= A \; T(k)_{max} \; (t_1 + t_2) + C. \quad (11)$$

This can be solved for t_1, so that the second exposure time is given by

$$t_2 = \left[(D(k)_{max} - C)/A \; T(k)_{max} \right] - t_1. \quad (12)$$

Then, for the variable-contrast edges, Eqs. (5), (8) and (12) determine the parameters necessary for controlled production.

Constant-Contrast Edges

Place a five-step tablet of aluminum foil layers over a piece of film and expose to x-rays for a time, t_1. The exposure on the film can be described by

$$^1E(k_i) = T(k_i)\ t_1, \tag{13}$$

where the superscript again denotes the first exposure series. The exposure history to this point is sketched in Figure 3a.

The x-radiation is then stopped and the step tablet removed. The tantalum strip is now laid along the film strip, approximately dividing the width of film in half. The film and tantalum strip are then exposed to the x-rays again, for a time, t_2. The second exposure adds another exposure to the format and can be described by

$$^2E(k_i) = t_2, \tag{14}$$

in those portions of the film that are not covered by the tantalum strip, and

$$^2E(k_i) = 0,$$

where the film is covered. These exposures add to the first; a summary of both is sketched in Figure 3b.

The density differences $\Delta D(k)$ produced by these exposures and the linear characteristic curve of Eq. (2) are given by

$$\begin{aligned} \Delta D(k) &= A\left\{T(k)\ t_1 + t_2\right\} + C - \left\{A\ T(k)\ t_1 + C\right\} \\ &= A\ t_2. \end{aligned} \tag{15}$$

This shows that the contrast of the edges is independent of the transmittances of the tablet steps, is constant, and is directly proportional to the second exposure time.

The second exposure time is determined first, and is obtained by inverting Eq. (15). Thus,

$$t_2 = \Delta D(k)/A, \qquad (16)$$

where $\Delta D(k)$ is constant, and specified according to requirements. At this point, the values of the five tablet steps can be specified. These will depend on the density values desired for the various portions of the edge-artifact. They will also depend on restrictions called for by the linear characteristic curve. Since ${}^1E(k_i) + {}^2E(k_i)$ will be the larger exposure,

$$D(k)_{max} = A \left\{ T(k)_{max}\, t_1 + t_2 \right\} + C \,. \qquad (17)$$

This can be solved for t_1, so that the first exposure time is given by

$$t_1 = \left[(D(k)_{max} - C)/A - t_2 \right] / T(k)_{max} \,. \qquad (18)$$

Then, for the constant-contrast edges, Eqs. (15), (16) and (18) determine the parameters necessary for controlled production.

Discussion I:

In order not to interfere with the orderly development of the theory relating exposure times and step tablet layers, the discussion of several restrictive relations was deferred. These have an important bearing on the eventual application of the technique and require an interpretive discussion that would have been distracting at the time.

For both artifacts, the second calculated exposure time depends on the previously-calculated exposure time and the maximum density of the linear characteristic curve, as can be seen in Eqs. (12) and (18). Since the first exposure times were determined from the specified contrast value (or the maximum of the three required for the VCE), it is possible to obtain negative values for the second calculated exposure times. Since they have no physical significance, it indicates a restriction on contrast as a function of maximum density. This can be seen from a consideration of Eq. (12), for the VCE artifact. So that t_2 not have a negative value, it is necessary that

$$(D_{max} - C)/A\ T(1) \geq t_1 \qquad (19)$$

Since t_1 was determined from Eq. (7) (using the high-contrast value, $\Delta D(k)_3$), we can insert it into Eq. (19), and obtain

$$D(k)_3 \leq D_{max} - C. \qquad (20)$$

With Eq. (18) for the CCEE artifact, it can be shown that the inequality of Eq. (20) also applies. Thus, for both artifacts, the upper limit to contrast (in terms of ΔD) is given by the difference of maximum density and base-plus-fog density.

In like manner, there is a minimum attainable contrast for the VCE artifact that stems from the method of determining the aluminum foil layers. The lowest contrast value and the exposure time are used to determine the appropriate T(k), from which the value of k is taken. This is stated in Eq (9). Since no more than 7 layers of foil are used (see the discussion of this in Appendix A), the smallest value of T(k) will be that equivalent to T(7). Thus, from Eq. (9), with the appropriate subscript,

$$D(k)_1/A\ t_1 \quad \leq \quad T(7). \tag{21}$$

When we replace the t_1 by the value determined in Eq. (8), we can see that

$$\Delta D(k)_1 \quad \leq \Delta D(k)_3 \cdot H, \tag{22}$$

where

$$H \quad = T(7)/T(1) \ . \tag{23}$$

Thus, the lowest contrast is limited not only by the specified high contrast value, but also depends on the effective transmittance factors of the aluminum foil. However, since the low contrast of the CCE artifact is independent of the step table, no practical lower limit to contrast exists for that artifact.

It is clear that the highest possible value of D_{max} must be determined for the material used in any application, since this clearly controls high contrast for both artifacts and the low contrast for the VCE. Experimentally, that value should be evaluated closely to give the technique as much contrast latitude as possible.

EXPERIMENT

To examine the limitations of the theoretical relations and to determine practical values for ranges of densities and contrasts that can be achieved by this technique, a limited experimental program was undertaken. The ultimate goal of the program is the production of edge-artifacts of prescribed properties, on film and glass plates. The experiments therefore concentrated more on the practical, engineering aspects of the problem and less on some others (e.g., the interesting analytical relation between the number of aluminum layers, x-ray exposure, and the corresponding effective transmittance factors).

Photographic Materials:

Kodak High Resolution Plates in the 1 x 3-inch size have been used since the early work and continue to provide an excellent image with x-rays.

The plates are nominally 0.060-inches thick. It was found that Kodak Spectroscopic Safety Film, Type 649-GH in 35mm width maintained the same image quality, although the film speed was reduced. Typical density versus exposure curves for these two materials, under the special exposure conditions for these experiments, are shown in Figure 1.

Photographic Processing:

Both films and plates are processed in Kodak HRP developer (1 part HRP diluted with 4 parts water) at 22°C, for 10 minutes. One plate or strip is processed at a time, in a tank, with constant, but extremely active manual agitation. Because of short-term latent image fading, processing always takes place within five minutes of the termination of exposure.

Subsequent fixing, washing and drying are sufficiently routine to warrant no additional comment. Densities are measured and corrected to diffuse (visual) density through calibration tables.

X-Ray Exposure:

The exposure device is a hybrid system consisting of an RCA Crystalloflex II power unit (built by Siemens) coupled through a cable to a General Electric CA-7 Collidge Tube having a copper target. The tube is mounted approximately 115 cm away from the photographic material and the beam expands to approximately 25 cm in the exposure plane. Exposure is made in the most uniform portion of that area. The unit is driven to 40 kV, at 10 mA, and holds constant for extended periods of time. However, it has been found expedient to achieve long exposures (on the order of 40 minutes) by breaking the total time into several shorter periods because of long-term power variations.

Aluminum Step Tablets:

The modulation of the x-rays to determine the density versus exposure curve and to provide the density steps for the edge-artifacts is accomplished by layers of aluminum foil. The material used in this investigation is commercially-available extra heavy Reynolds Wrap in a 1-mil thickness. A typical step tablet is shown in Figure 4.

Characteristic Curve for Film:

To determine the density-exposure characteristics for Kodak Spectroscopic Film, Type 646-GH, under the standard processing conditions previously cited, a series of exposures was made with the aid of a seven-step aluminum foil

tablet. These exposures were suitably replicated to assure reproducibility and establish the necessary statistics. Since the region associated with the unmodulated 20-minute exposure is near the end of the linear range (and therefore most useful for producing the higher densities), it was given additional weighting in the analysis provided by the program described in Appendix B. Three exposure groups were included at or near 20 minutes. The resulting characteristic curve is shown in Figure 5. The constants of the curve and the transmittance factors of the aluminum steps are shown in Table I. From these values, the exposure times and step table layers necessary to produce both types of edge-artifact on film can be determined.

Two Edge-Artifacts on Film; Typical Calculations:

For the variable-contrast edges, we specify three contrasts 0.5, 1.0 and 1.5. With the aid of Eq. (7), we set up the following table:

$\Delta D(k)_i$	$\Delta D(k)_i/A$
1.5	16.1
1.0	10.7
0.5	5.3

The value of the constant, A, is given in Table I. We choose to have the highest contrast correspond to k = 1 (for reasons to be discussed shortly), so that t_1 is determined by

$$t_1 = \Delta D(k)_3/AT(1) = (16.1)/(0.68) \simeq 24 \text{ minutes.}$$

The value of T(1) has been taken from the listing of Table I. If we now utilize Eq. (9) to determine the corresponding k_i for the other contrasts, we have

$$T(k)_2 = \Delta D(k)_2/At_1 = (10.7)/(24) = 0.45 \longrightarrow T(2),$$

so that $k_2 = 2$.

In a similar manner we can show that for the remaining step, $T(k)_1$ is approximated by T(5), and k_1 thus has a value of 5.

Study of the plot in Figure 5 shows that a comfortable D_{max} is 2.0. Then the second exposure time can be calculated from Eq. (12), and for these parameters it can be shown that

$$t_2 \simeq 7 \text{ minutes.}$$

Because we have taken the maximum density (2.0) and related it to k = 1, the density that will correspond to an exposure for k = 0 may be off the linear portion of the curve and thus can only be estimated. But this

necessary exposure will provide a density higher than the highest edge-density, as required for instrumental calibration with eventual use. For the first and fifth tablet steps, therefore, we choose k = 0 and k = 7, respectively. The step tablet makeup and the exposure history for this artifact are shown in Table II, together with the predicted densities calculated from Eq. (2). In this instance, and for all the other calculations in this section, exposure times are rounded-off to the nearest minute. Since these examples are intended to be illustrative, it is felt that further precision is not warranted.

For the constant-contrast edges, we specify a contrast of 1.0. Since the contrast is independent of the table steps, we choose to use the same set of five transmittances used for the variable-contrast edges; i.e., k = 0, 1, 2, 5, and 7. From Eq. (16) and the value of A from Table I, we can determine the second exposure time.

$$t_2 = \Delta D(k)/A = 1/(0.09345) \simeq 11 \text{ minutes.}$$

From Eq. (18), the first exposure time can be calculated, and it can be shown that for these parameters,

$$t_1 \simeq 15 \text{ minutes,}$$

where, as in the previous calculation, D_{max} is taken to be 2.0, and the exposure times have been rounded off to the nearest minute. The step tablet makeup and the exposure history for this artifact are shown in Table III, together with the predicted densities calculated from Eq. (2).

Characteristic Curve for Plates:

To determine the density-exposure characteristics of Kodak High Resolution Plates under the processing conditions previously cited, a series of exposures was made with the aid of a seven-step aluminum foil tablet. These exposures were made at 2, 5, 10 and 15 minutes. The region associated with the 10-minute unmodulated exposure was given additional weight since it is near the end of the linear position of the curve.

The resulting characteristic curve is shown in Figure 6. The constants of the curve and the effective transmittance factor of the aluminum steps are shown in Table IV. From these values, the exposure times and step tablet layers necessary to produce both types of edge-artifact on film can be determined.

Two Edge-Artifacts in Glass Plates:

The necessary exposure times and step table specifications for glass plates are calculated exactly as done previously for the film except that the characteristic curve parameters are different. Using the values of T(k) and A for the listing in Table IV, a variable-contrast edge-artifact is calculated and the exposure history and step tablet makeup are shown in Table V. Corresponding calculations for the constant-contrast artifact are shown in Table VI.

Results:

The edge-artifacts described in Tables II, III, V and VI were exposed and processed according to the exposure times and step tablet transmittances specified. To illustrate the process, one of each was made; measured densities are shown in Table VII for all four artifacts, together with the actual density differences (ΔD) that measure contrast. For each artifact, the table that described exposure and predicted density is cited in the heading. Figure 7 contains a photograph of some of these artifacts.

Study of the actual density values (compared to those predicted) shows that the densities are (with one exception) within the 3-sigma limits for the materials, and the contrasts are close to specification. The one significant discrepancy is associated with the variable-contrast edges on glass plates. There, the actual densities are much larger than those predicted, but the predicted contrasts are amazingly close. This particular artifact dropped out of its hanger while being processed, was manually replaced and the processing continued to completion. It thus received different agitation from the standard conditions (possibly a slight temperature increase). Normally, such an artifact would be discarded and another exposed and processed properly. However, it is included here because the densities are apparently on the correct (linear) characteristic curve (since the contrasts were so close to the expected values). This indicates that the linear curve probably extends to densities beyond 2.20.

Since these artifacts were intended to serve primarily as a demonstration of the process, they were not replicated sufficiently to establish a basis for statistical study of the process. The need for production of specific contrasts within tight tolerances has not been established as yet, and because of this there is simply insufficient justification to establish process statistics at this time.

Because the techniques for obtaining sharp edges with this method had already been developed and since the purpose of this investigation was the development of exposure techniques to produce the two specific artifacts, no particular attention was paid to the achievement of edge-sharpness, per se. Nevertheless, in a check of the process, the variable-contrast edges on film listed first in Table VII were scanned on the Mann-Data Microanalyzer at NBS.

The criterion used at NBS for determining the edge quality is the mean-squared slope of the edge-trace, measured between two points and corrected for density. When these points are on the upper and lower extremities of the edge (where the value of the slope is 0.005 density units/μm) and the density correction is accomplished by inserting the value of ΔD in the denominator, the quantity determined is equivalent to the acutance developed by Higgins and Jones[1]. In this instance, since the edge is of such high quality, the response of the microdensitometer is incorporated

in the resultant equivalent acutance value. Typically, ΔD's of 1.5 at mean densities in the range of 1.2 to 1.5 produce equivalent acutance values of approximately 50,000 (density units/μm^2) when evaluated on the Microanalyzer with a 2 x 100-μm sampling aperture[12], overfilled optics, image scanning and an efflux numerical aperture of 0.25.

The high-contrast step of the artifact tested (ΔD = 1.35, from Table VII) had a measured equivalent acutance of 48,400. This is essentially at the same level of quality as that obtained previously with the process, so that the new exposure method(s) has apparently not caused any deterioration.

DISCUSSION

From a study of the results of Table VII, it is clear that the process is well-characterized by the linear theory, and might be made more reproducible if the procedures were more controlled. However, there are inherent limitations to both the process and the analysis that need further discussion before an assessment of possible improvement or wide-scale production is carried out.

During the preliminary determinations that led to the linear characteristic curve, it was found that the slope of the curve was sensitive to exposure level; i.e., exposure of the emulsions in different parts of the beam led to different values of slope. It was found necessary to use only one portion of the beam for both step tablet exposure (for the curve-determination) and for the final edge/table artifact exposures. It was presumed that this resulted from an unevenness of illumination within the beam. As long as the radiation level in that region remined constant, there was no variation in system characterization. Failure to relocate the materials properly in the exposure phase results in a change in sensitometry.

When the photographic process employs the linear portion of the density versus log-exposure curve (the region of usage in nearly all applications), the slope or "gamma" of the curve is independent of exposure. Even with toe exposures, one can expect that for identical processing times and procedures, the slope should be exposure-independent and be only a function of the properties of the material. However, in this case, because of the exposing radiation and the peculiar attenuating response of the aluminum foil layers, this relation is apparently altered and made dependent on exposure level. Inasmuch as all the interactive factors have been inextricably lumped together, it is difficult to explain this dependence satisfactorily. The effect can be treated phenomenologically, and the problem obviated by fixing the position of the materials and associated apparatus in one portion of the exposing beam.

The combined analytical determination of the characteristic curve and the effective transmittance factors of the aluminum step tablet leads to an interesting variation in the attenuation afforded by the aluminum foil; it is as much a property of the process as it is of the material itself. Tables I an IV show that the T(k)'s for the high resolution plates are higher than the corresponding T(k) for the spectroscopic safety film for a given k ($k \neq 0$). This is a direct and result of lumping together the effects of film speed, tablet attenuation and exposure and processing of the material for the toe of the normal characteristic curve. The variation in transmittance factors should not be construed as an inadequacy of the model, but rather as an indication of the flexibility of the approach and a tacit warning that the total process and procedure must remain fixed for a given material.

The densities on the lower portion of the density versus exposure curve (below a density of approximately 1.0) are relatively easy to control and reproduce, while those above this value manifest a much wider variation and are difficult to obtain in a reproducible manner. This is typified in the plots of Figures 5 and 6. This wider variation occurs primarily because this is the region of the particular material's response where high-contrast imagery inherent in these materials is beginning to manifest itself. The slope of the normal characteristic curve is extremely high for these processing conditions, and with a virtually negligible toe region, the minutest variation in processing conditions (such as temperature, agitation, solution concentration) or exposure is often reflected in a large density variation. Thus, it is difficult to control densities near the end of the linear density-exposure curve, and it is in these very values that the largest deviations from the specifications of Tables II, III, V and VI are evident in the edge-artifacts listed in Table VII. As a result of this inherent process-limitation, the attainment of a given set of densities and contrasts in a single trial is highly unlikely. If there is a significant restriction to the production of specific artifacts, it lies in this problem area, and in the absence of more stringent process-control, normal scatter among many trials must be depended upon to meet a specified set of parameters; i.e., given enough replications of the same exposure history and processing, one artifact will eventually emerge that is very close to the specified characteristics.

Since the production of the artifacts for this report was primarily for illustrative purposes, the exposure times were rounded to the nearest minute. In actual practice, they would probably be rounded to the nearest quarter-minute, perhaps to the nearest 2/10-minute, since there is more control over the exposure time than over the layers of aluminum foil (which are limited to seven, presently). Because of the necessity for an integral number of layers of this foil, the attainment of exact contrast for each step in the variable-contrast edge-artifact is highly improbable. The time chosen for the first of these (the highest contrast

step) allows precise achievement of that contrast; the remainder depend on how closely the available step transmittances approximate the required values. Some trade-off is possible, but it will be difficult to obtain all three contrasts exactly. On the other hand, since the contrast of the constant-contrast artifact is determined solely by the second exposure time, actual edge-contrast on this artifact can probably be made artitrarily close to specifications.

CONCLUSIONS

There is presently no requirement for specific contrasts for either artifact type. The values used in this report therefore are as representative of the process as any others, and will temporarily serve as "standard" values. Since the process is capable of producing the edge-artifacts on demand, NBS does not plan to stock large amounts of these artifacts. The calculations for any specific requirement are trivial (and can easily be computerized, to minimize time and cost) and the procedures sufficiently standardized to respond rapidly to any request.

ACKNOWLEDGMENT

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TABLE I

Constants for use with Kodak Spectroscopic Film, Type 649-GH, with standard processing conditions

Linear Characteristic Curve

A	=	0.09345
a_1	=	0.38314
a_2	=	0.02030
C	=	0.04

Effective Aluminum Step Tablet Transmittance Factors

k	T(k)
0	1.00000
1	0.68172
2	0.48400
3	0.35786
4	0.27556
5	0.22098
6	0.18456
7	0.16052

TABLE II

Exposure History and Calculated Densities
for the Variable-Contrast Edges on Film

Step Tablet (Number of aluminum foil layers):

0	1	2	5	7

First Exposure: t_1 = 24 minutes; $E(k)_1 = t_1 T(k)$.

24.00	16.36	11.62	5.30	3.85
0	0	0	0	0

Second Exposure: t_2 = 7 minutes; $E(k)_2 = t_2 T(k)$.

31.00	21.13	15.01	6.85	4.97
7.00	4.77	3.39	1.55	1.12

Calculated Densities (by Eq. (2), constants from Table I):

3.0	2.01	1.44	0.68	0.50
0.69	0.49	0.36	0.18	0.14

		↑	↑	↑
ΔD	⟶	1.52	1.08	0.50

TABLE III

Exposure History and Calculated Densities
for the Constant-Contrast Edges on Film

Step Tablet (Number of aluminum foil layers):

0	1	2	5	7

First Exposure: t_1 = 15 minutes; $E(k)_1 = t_1 T(k)$.

15.00	10.22	7.26	3.31	2.41

Second Exposure: t_2 = 11 minutes; $E(k)_2 = t_2$.

26.00	21.22	18.26	14.31	13.14
15.00	10.22	7.26	3.31	2.41

Calculated Densities (by Eq. (2), constants from Table I):

2.5	2.02	1.75	1.38	1.29
1.44	1.00	0.72	0.35	0.26
	↑	↑	↑	
ΔD ⟶	1.02	1.02	1.03	

TABLE IV

Constants for use with Kodak High Resolution Plates
with standard processing conditions

Linear Characteristic Curve

A	=	0.19856
a_1	=	0.32739
a_2	=	0.01815
C	=	0.06

Effective Aluminum Step Tablet Transmittance Factors

k	T(k)
0	1.00000
1	0.72080
2	0.53876
3	0.41758
4	0.33563
5	0.27973
6	0.24176
7	0.21667

TABLE V

Exposure History and Calculated Densities
for the Variable-Contrast Edges on Glass Plates

Step Tablet (number of aluminum foil layers):

0	1	2	5	7

First Exposure: t_1 = 10 minutes; $E(k)_1 = t_1 T(k)$.

10.00	7.21	5.39	2.80	2.17
0	0	0	0	0

Second Exposure: t_2 = 4 minutes; $E(k)_2 = t_2 T(k)$.

14.00	10.09	7.54	3.92	3.04
4.00	2.88	2.15	1.12	0.87

Calculated Densities (by Eq. (2), constants from Table IV):

2.6	2.06	1.56	0.84	0.66
0.85	0.63	0.49	0.28	0.23
	↑	↑	↑	
ΔD ⟶	1.43	1.07	0.56	

TABLE VI

Exposure History and Calculated Densities
for the Constant-Contrast Edges on Glass Plates

Step Tablet (number of aluminum foil layers):

0	1	2	5	7

First Exposure: t_1 = 7 minutes; $E(k)_1 = t_1 T(k)$.

7.00	5.05	3.77	1.96	1.52

Second Exposure: t_2 = 5 minutes; $E(k)_2 = t_2$.

12.00	10.05	8.77	6.96	6.52
7.00	5.05	3.77	1.96	1.52

Calculated Densities (by Eq. (2), constants from Table IV):

2.5	2.06	1.80	1.44	1.35
1.45	1.06	0.81	0.45	0.36
	↑	↑	↑	
ΔD ⟶	1.00	0.99	0.99	

TABLE VII

Typical Experimental Edges

Variable-Contrast, on Film (See Table II):

2.63	1.89	1.36	0.65	0.49
0.75	0.54	0.38	0.21	0.17

$\Delta D \longrightarrow$ 1.35 0.98 0.44

Constant-Contrast, on Film (See Table III):

2.53	2.10	1.83	1.47	1.35
1.54	1.07	0.76	0.37	0.28

$\Delta D \longrightarrow$ 1.03 1.07 1.10

Variable-Contrast, on Glass Plates (See Table V):

3.07	2.20	1.66	0.86	0.65
1.11	0.76	0.58	0.30	0.24

$\Delta D \longrightarrow$ 1.44 1.08 0.56

Constant-Contrast, on Glass Plates (See Table VI):

2.60	2.06	1.88	1.52	1.44
1.65	1.11	0.85	0.44	0.34

$\Delta D \longrightarrow$ 0.95 1.03 1.08

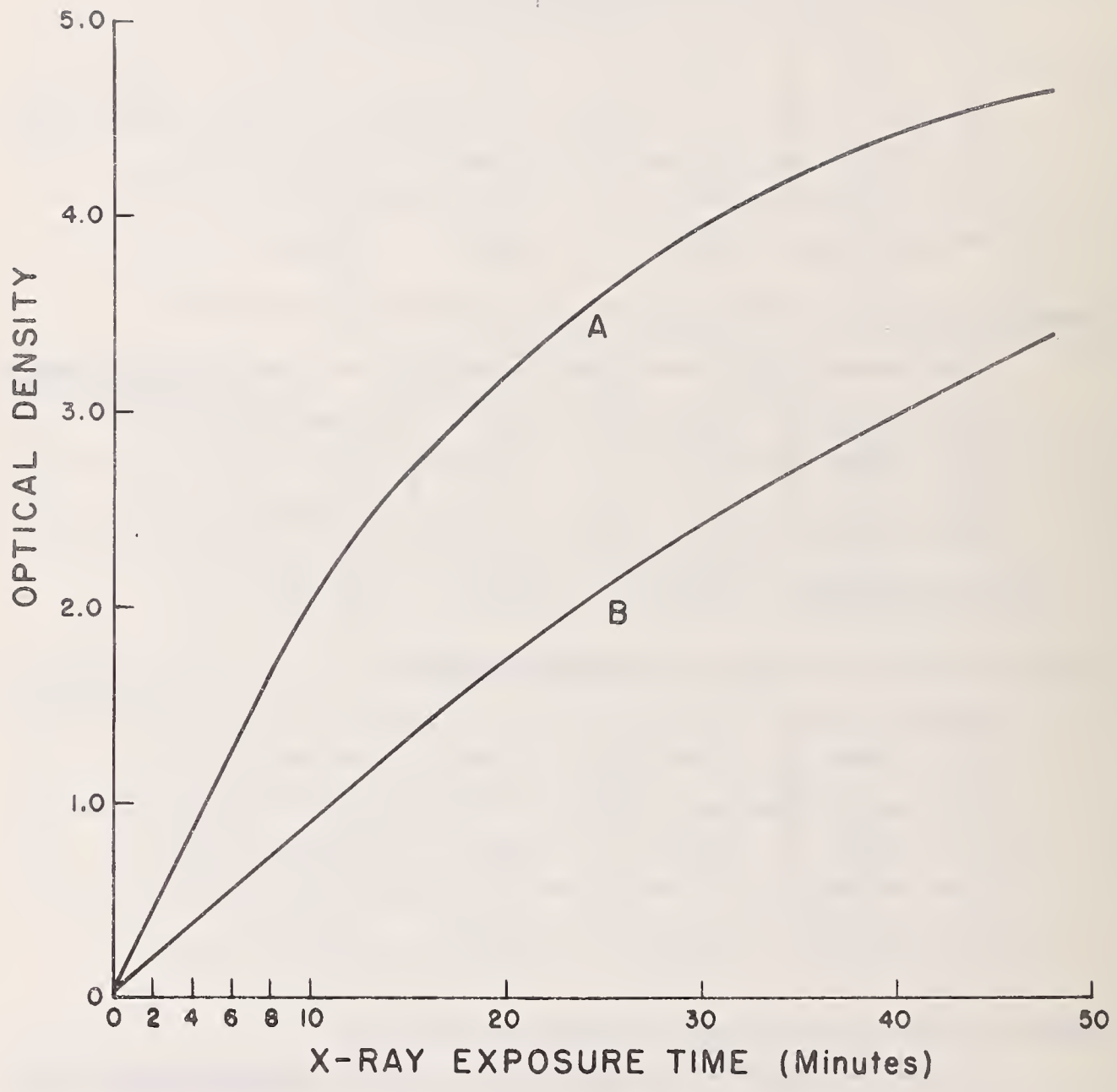

Figure 1: Typical density versus exposure curves for high resolution materials exposed to x-rays. In these curves, the source intensity remained constant while the exposure time was varied (no step tablets in use). The curves are linear to a density value of 2.0. A: Kodak High Resolution Plates; B: Kodak Spectroscopic Saftey Film, Type 649-GH.

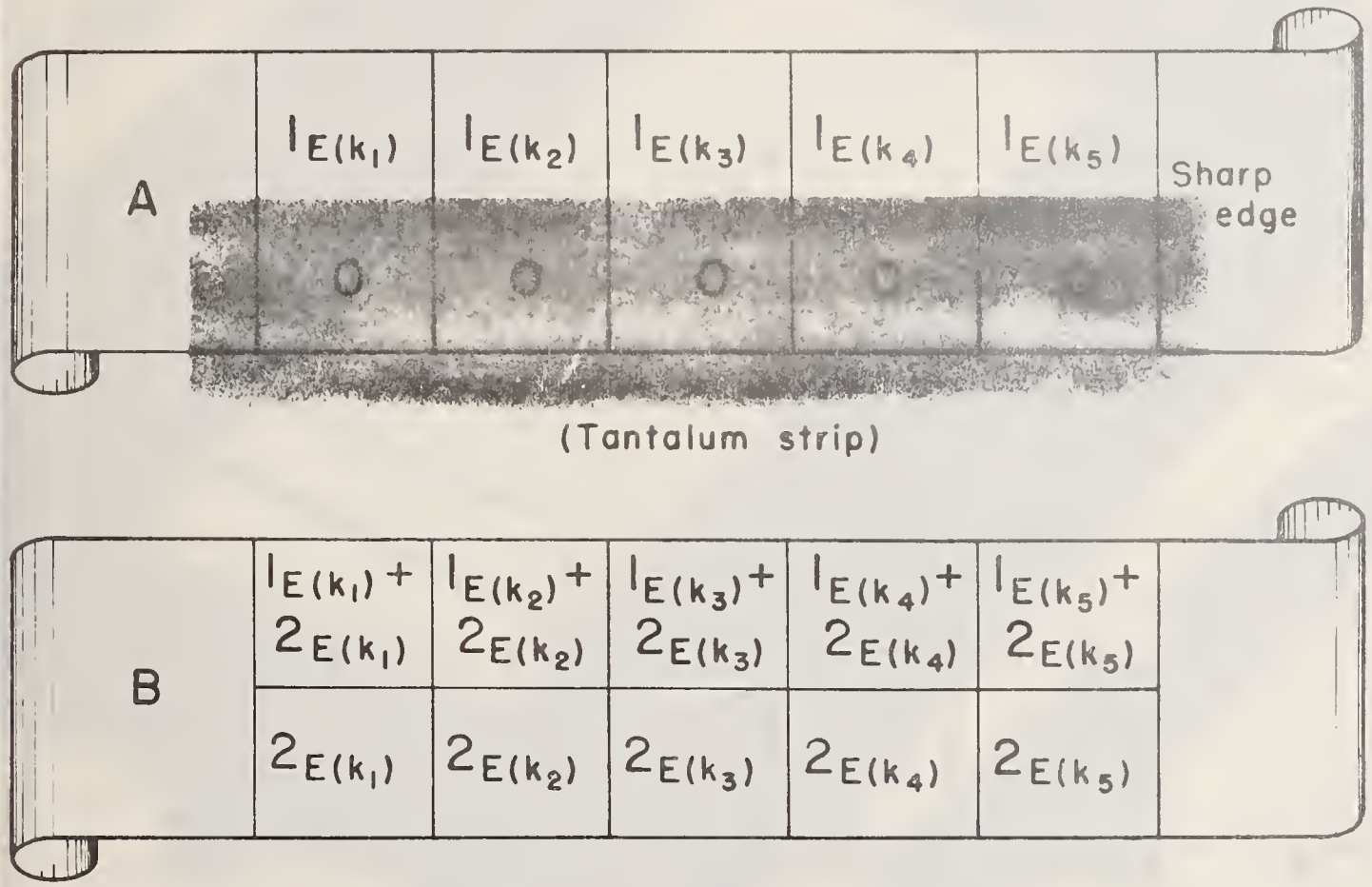

Figure 2: Summary of exposure history for variable-contrast edges;

A: After first exposure (with tantalum strip and step tablet in place).

B: After second exposure (step tablet in place, tantalum strip removed).

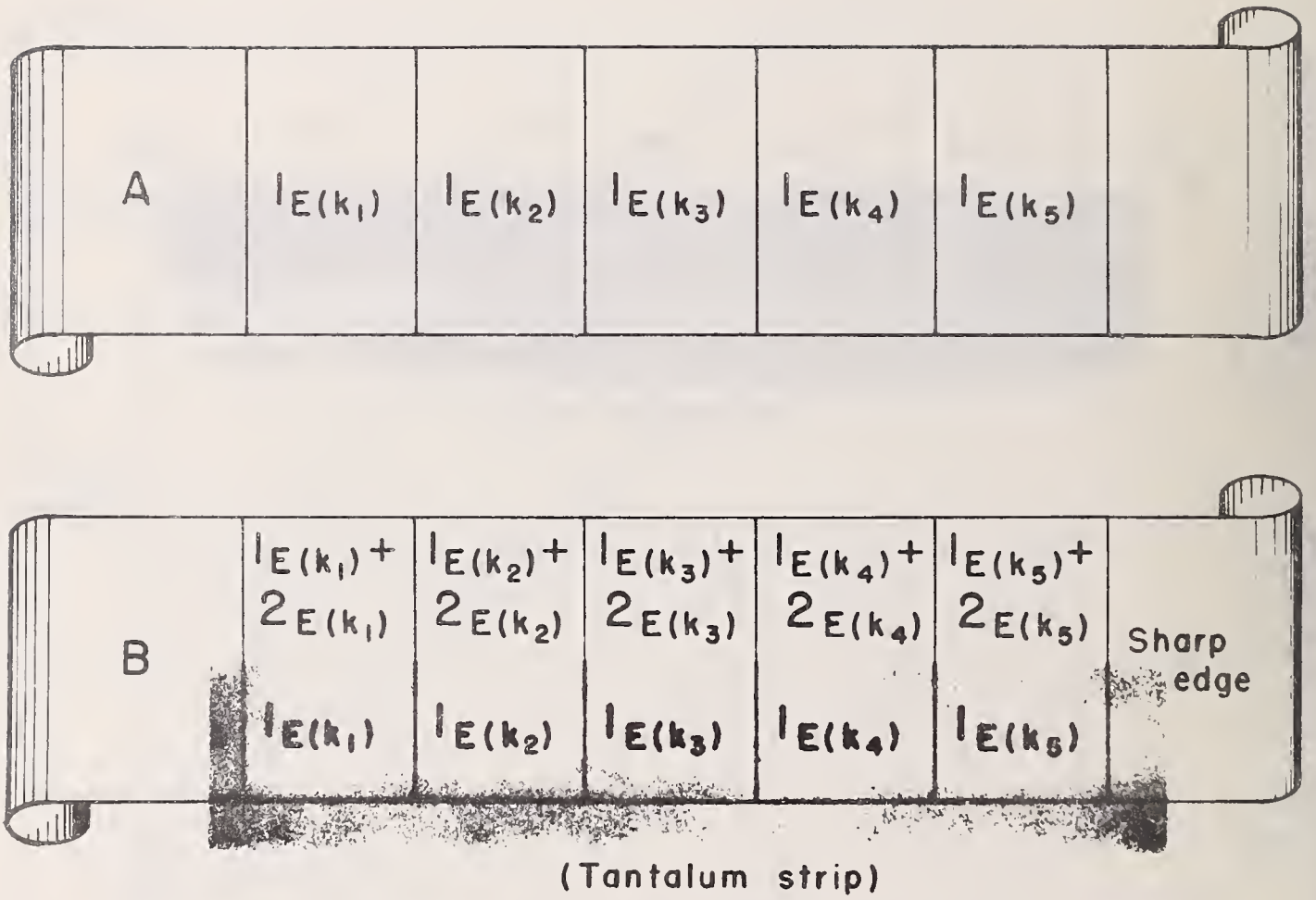

Figure 3: Summary of exposure history for constant-contrast edges;

A: After first exposure (step tablet alone).

B: After second exposure (step tablet removed, tantalum strip in place).

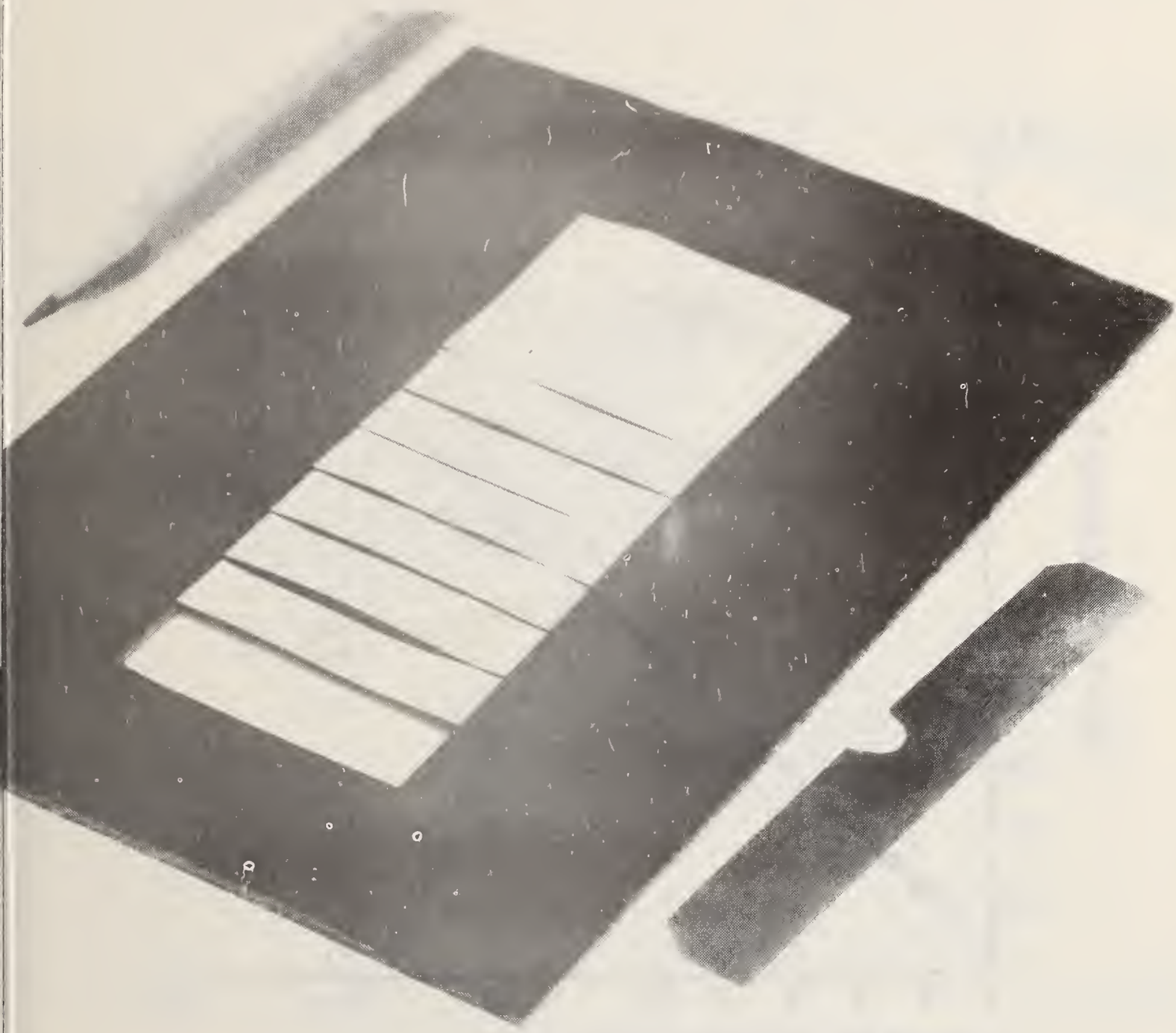

Figure 4: Two exposure aids used in the production of edge-artifacts. On the right is the tantalum strip used to produce the sharp edge-discontinuity. The right edge of the strip has received a metallographic polish. On the left is a typical 7-step tablet of aluminum foil layers. In use, the layers are tightly compacted; here they have been slightly separated to exhibit the format. Typical transmittance factors for such a tablet with x-rays are shown in Tables I and IV.

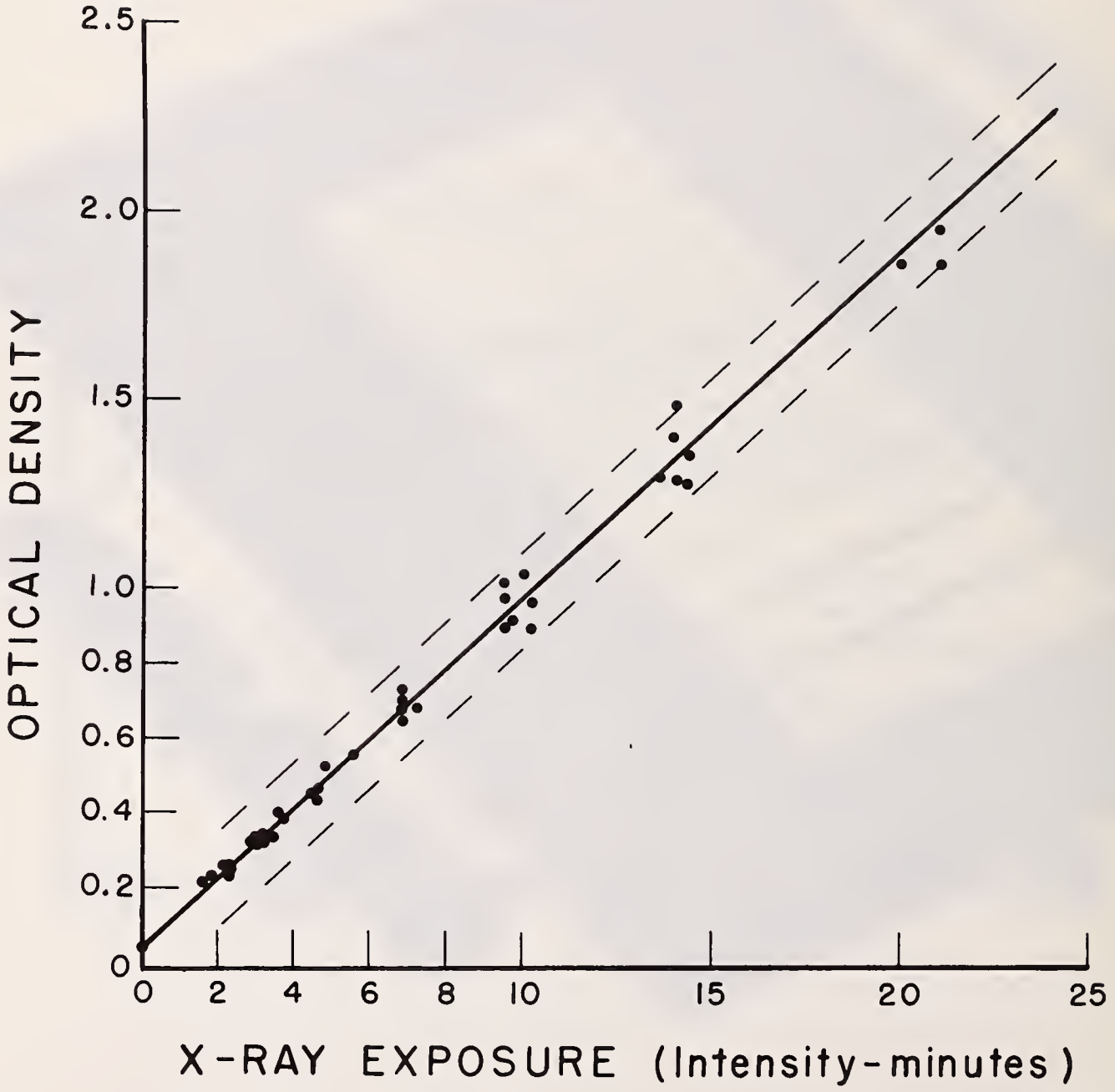

Figure 5: Linear characteristic curve for Kodak Spectroscopic Safety Film, Type 649-GH (35 mm size), processed in HRP (1:4) at 22°C for 10 minutes with constant agitation. The 3-sigma limits on density are shown as dashed lines. The curve is linear out to at least a density value of 2.0.

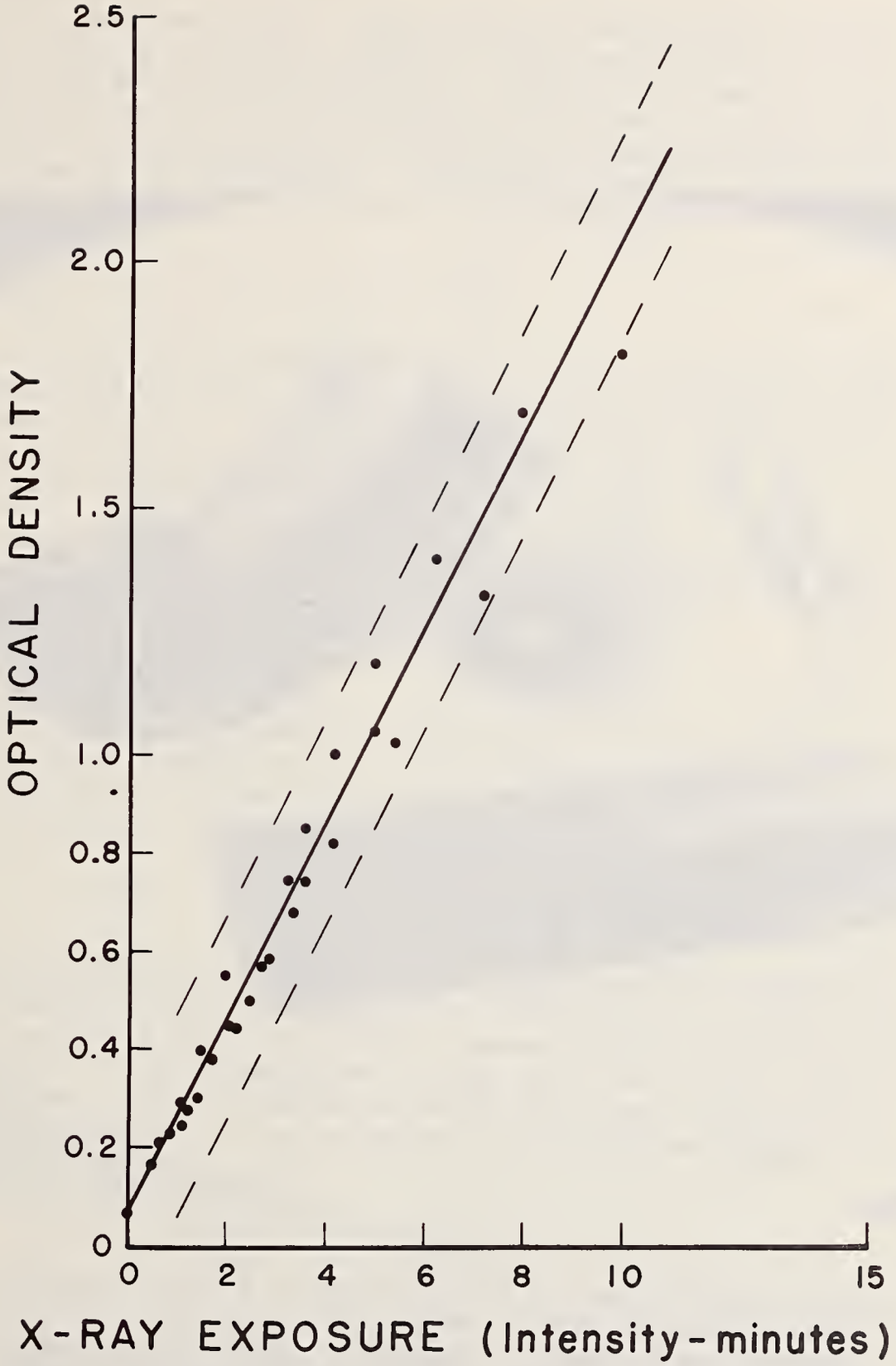

Figure 6: Linear characteristic curve for Kodak High Resolution Plates, processed in HRP (1:4) at 22°C for 10 minutes with constant agitation. The 3-sigma limits on density are shown as dashed lines. The curve is linear out to at least a density value of 2.0.

Figure 7: Typical edge-artifacts. Topmost is the constant-contrast version on film; the other is the variable-contrast version on glass plate. The three edges of interest on each are in the center, flanked by larger areas of density (one of which is ordinarily used for identifying purposes, as illustrated). The sharp discontinuity runs lengthwise and a scan of these edges (on a microdensitometer, for example) would run across this.

APPENDIX A: Sensitometry with aluminum foil step tablets

In general sensitometry, step tablets are often used to provide a modulation of exposure for a given exposure time. In the present system, because of the exposing radiation, layers of aluminum foil are a convenient means for achieving the required modulation. Careful experimentation has disclosed that the x-ray exporsure produced through these aluminum layers is not only proportional to the total thickness (exponential absorption) but is also a function of scattering. It has been found that the effective transmittance of k layers of uniform foil thickness is given by the expression

$$T(k) = \exp\left[-(a_1 + a_2)k + a_2 k^2\right]. \qquad (A\text{-}1)$$

The constant factors in this expression depend on the material (aluminum in this instance) and the type of exposing x-radiation. Inasmuch as the effective transmission is also related to the photographic material and its processing to a certain extent, the constants must be determined experimentally, for each emulsion type†.

The linear relation between density and exposure for the x-radiation and high resolution emulsion processed and exposed for utilization of the toe region is described by

$$D(k) = A\,E(k) + C, \qquad (A\text{-}2)$$

where C is the base-plus-fog density and E(k) is the exposure produced through k thicknesses of aluminum foil. The constant, A, incorporates such considerations as exposing intensity and film speed. In terms of tablet transmittance and exposure time, we can write

$$D(k) = A\,T(k)\,t = C, \qquad (A\text{-}3)$$

†This expression clearly has a limited range of applicability, inasmuch as the positive contribution in the exponential will eventually overtake the negative, due to the k^2 term, and produce transmittances in excess of unity. Thus, the function has a minimum value, beyond which the physics cannot be safely interpreted. This minimum value can be determined through the differential calculus, and is can be shown that the maximum integer value of k is given by

$$k_{max} = \text{Int}\left[(a_1 + a_2)/(2a_2)\right].$$

For the data of Tables I and IV (coincidentally), k has a maximum value of 9. By limiting the experimental determinations of transmittance and the eventual exposure usage of the aluminum to 7 layers (i.e., k = 7), this inherent limit is not reached and we can retain confidence in the efficacy of Eq. (A-1) to characterize the transmittance of the aluminum step tablets.

where t is the exposure time. To determine the characteristic curve for the material and ascertain the constants a_1 and a_2 necessary to describe T(k), we make a series of exposures through an aluminum step tablet. We then process the photographic material and measure the corresponding densities for each tablet step. Thus, in Eq. (A-3), we know D(k), k, t and C from experiment. With these we can determine A and T(k) through analysis, we first conbine Eqs. (A-1) and (A-3) and rearrange some of the terms. Thus,

$$(D(k) - C)/t = A \exp\left[-(a_1 + a_2)k + a_2k^2\right]. \qquad (A\text{-}4)$$

When we take the natural logarithm of both sides of this equation, we obtain

$$\log_e\left\{D(k) - C)/t\right\} = \log_e(A) - (a_1 + a_2)k + a_2k^2 , \qquad (A\text{-}5)$$

and this reduces to the relation

$$y = b_2k^2 + b_1k + b_o, \qquad (A\text{-}6)$$

where

$$y = \log_e\left\{(D(k) - C)/t\right\}; \qquad (A\text{-}7)$$

$$b_o = \log_e(A);$$

$$b_1 = -(a_1 + a_2);$$

$$b_2 = a_2.$$

Eq. (A-6) is a quadratic in k that can be fitted to the experimental data by the method of least squares. This determines the fit-constants, b_o, b_1, and b_2. From these values, we can obtain the constants of the characteristic curve through

$$A = \log_e^{-1}(b_o) = \exp(b_o);$$

$$a_1 = -(b_1 + b_2); \qquad (A\text{-}8)$$

$$a_2 = b_2.$$

With these parameters, it is then possible to calculate, through Eq. (A-1), the effective transmittance of the layers of aluminum in each step. Subsequently we can convert the input values of exposure time and T(k) to exposure and plot them (if required).

It is useful to have a measure of how well the function and the experimental data are related. In statistical analysis this is usually accomplished by calculating a coefficient of correlation[13]. This is a parameter that lies within the limits of 0 and 1, the latter denoting a perfect relationships, the former, none at all.

For any curve, the index of correlation is given by

$$\rho_{xy} = \sqrt{1 - S_y^2 / \sigma_y^2} \quad , \qquad \text{(A-9)}$$

where

ρ_{xy} = index of correlation for two variables, x and y;

S_y = standard error of estimate ;

σ_y = standard deviation of the y-variable.

It can be shown that the standard error of estimate is given by

$$S_y = \sqrt{\sum \rho^2 / N} \, , \qquad \text{(A-10)}$$

where

N = number of experimental points;

$\sum \rho^2$ = sum of the squares of the y-residuals.

For the curve of Eq. (A-6), the i^{th}-residual is given by

$$\rho_i = y_i - b_2 k_i^2 - b_1 k_i - b_o \, .$$

When the various equations are combined, using the known relations for standard deviation, the index of correlation is given by

$$\rho_{y,k} = \sqrt{1 - \sum \rho_y^2 / \left[\sum y^2 - (\sum y)^2 / N\right]} \, . \qquad \text{(A-12)}$$

Knowledge of $\rho_{y,k}$ will give us an indication of the verisimilitude of the functional relation of Eq. (A-6) and a measure of the experimental measurement accuracy.

However, the correlation index applies strictly to the y-relationship defined in Eq. (A-7). This is a logarithmic quantity which is less sensitive to variation than optical density. The index is a good measure of the curve-fit, particularly since it gives confidence in the values of T(k) subsequently calculated. However, it is more useful to have a measure of the spread of density values about the linear curve after the exposures have been calculated. The usual estimates of this spread are the 3-sigma (standard deviation) limits: this establishes limits within which 99% of the data lie. It can easily be determined when the input density and calculated input exposure are listed, by applying standard statistical procedures to the information.

The program DOODAH was written to carry out all these calculations, and a listing, documentation and typical output are shown in Appendix B. The characteristic curve derived from that program is plotted in Figure (A-1). The experimental points are shown on the plot to illustrate the high correlation index value of 0.9989 calculated for these data and curve.

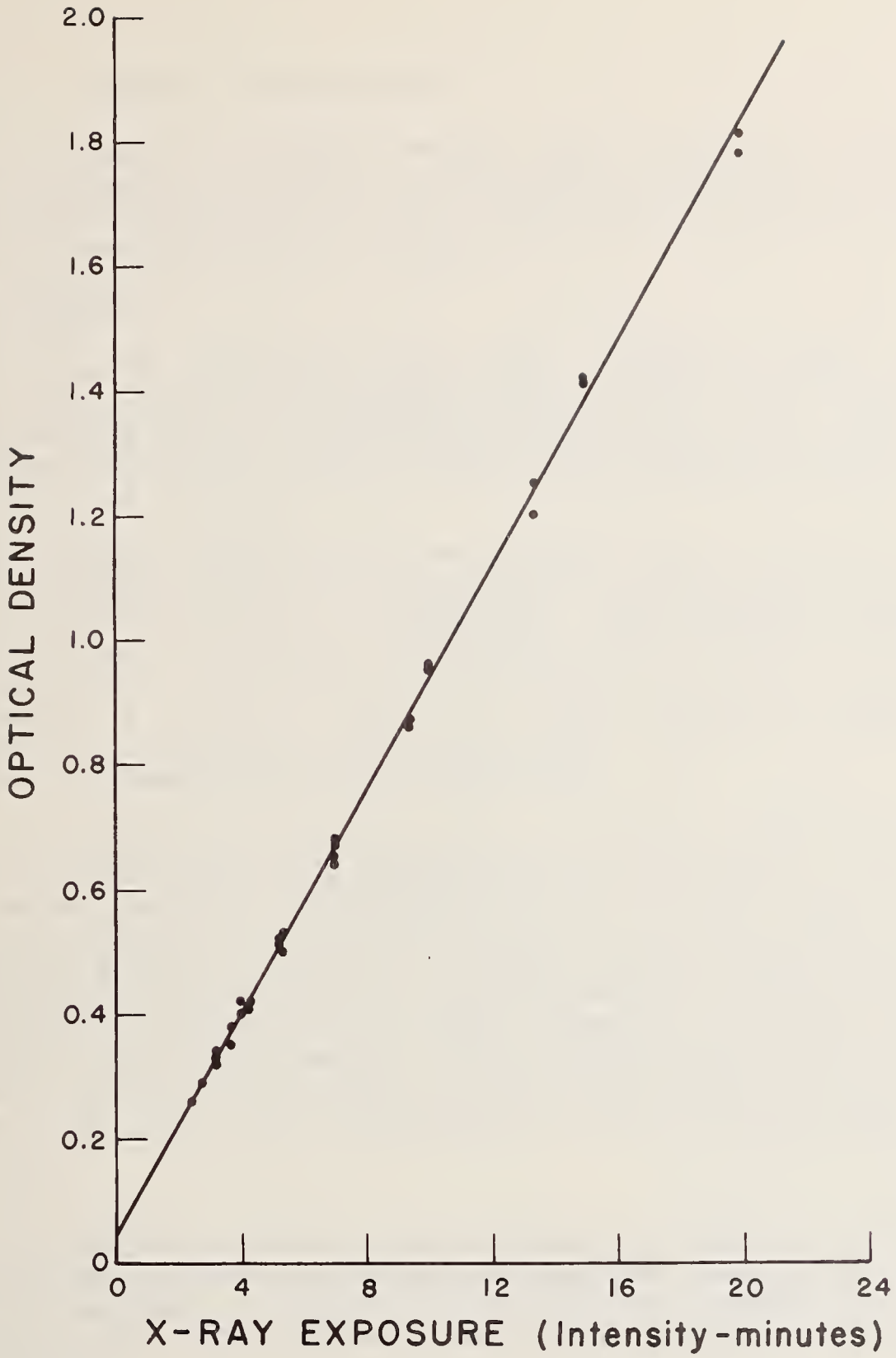

Figure A-1: Typical sensitometric curve for high resolution material exposed to x-rays, exposed and processed to utilize the toe region of the normal (logarithmic) characteristic curve. Experimental points are indicated. the 3-sigma limits on density for this distribution are ±0.05.

APPENDIX B: Computer program DOODAH

DOODAH is a program in the BASIC language that calculates the various parameters necessary to characterize the system sensitometry. It uses experimental data and carries out the calculations with the aid of the fundamental equations derived in Appendix A.

Program Synopsis:

Data is entered in lines 905 and subsequent, in groups of three: exposure time (T), the number of aluminum foil layers in tablet step (K) and the measured density of that corresponding step (D1); e.g., 20, 5, 0.44. Line 900 contains the number of groups of data and the measured base-plus-fog density (C); e.g., 32, 0.04.

After the headings are printed and the matrices zeroed, the data is read into the program, a listing is printed and the various matrix elements are computed and stored (Lines 065 through 145). These elements are the coefficients required for the least-squares curve-fit which culminates in lines 148 and 152. Subsequently, the fit-constants are used to calculate the parameters A, a_1 and a_2 (Lines 156 through 158) that are required to calculated the transmittance of the steps, T(k), and to convert the input data (K,T) to exposure (lines 809 through 844).

The fit-constants (b_o, b_1 and b_2) and the constants of the characteristic curve (A, a_1 and a_2) are then listed (Lines 175 through 190). Following this, the coefficient of correlation is calculated and printed. At this point the transmittance of each of the steps is calculated and printed. The table so produced is useful for reference when determining the final exposures for the edge-artifacts. Finally, the input values of K and T are converted to exposure and a listing of density (D1) versus exposure is printed (Lines 836 through 860). This provides experimental points that can be plotted with the fitted curve to illustrate the sensitometric relation. The value of the 3-sigma limit is then calculated and printed.

The Listing:

The program DOODAH is listed on the following three pages. The complete program output (derived from the data in lines 900 through 919) is then listed and annotated. A plot of the density versus exposure data found on the last page of this listing is the typical characteristic curve shown in Appendix A.

```
001 * RICHARD E. SWING, 213.11,X2159, PROGRAM: DODAH
002 *
003 * THIS PROGRAM IS USED TO DETERMINE EXPOSURE-DENSITY
004 * RELATIONS FOR THE X-RAY EXPOSURE AND PHOTOGRAPHIC PROCESS-
005 * ING OF NBS EDGE-TARGETS.  INPUT DATA ARE ENTERED IN GROUPS
006 * OF THREE: EXPOSURE TIME (T), NUMBER OF ALUMINUM LAYERS IN
007 * TABLET STEP (K) AND THE MEASURED DENSITY OF THAT STEP (D1).
008 * PROGRAM FITS DATA TO CURVE, DISPLAYS THE CONSTANTS, CALCULA
009 * THE CORRELATION COEFFICIENT, COMPUTES AND DISPLAYS THE
010 * TRANSMITTANCE OF THE ALUMINUM LAYERS AND CALCULATES THE
011 * EXPOSURES NECESSARY TO PLOT THE INPUT DATA.  INPUT IS LIMIT
012 * TO 75 TRIPLES OF DATA UNLESS ARRAYS ARE ENLARGED.
013 *
020 DIM A(2,2),L(2,2),B(2,0),S(2,0)
022 DIM W(75),X(75),Y(75),P(75)
030 FOR J = 1,5
035 PRINT
040 NEXT J
042 GOSUB 750
044 MAT B = ZER
045 MAT A = ZER
050 MAT S = ZER
052 S = 0
055 GOSUB 400
065 READ N,C
070 FOR J = 1,N
072 READ T,K,D1
073 W(J) = T
074 X(J) = K
075 Y(J) = D1
077 D = (D1-C)/T
078 S = S+(LOG(D))**2
080 A(0,1) = A(0,1) + K
085 A(1,2) = A(0,1)
090 A(0,0) = A(0,0) + K**2
100 A(2,2) = A(0,0)
105 A(1,1) = A(0,0)
110 A(1,0) = A(1,0) + K**3
115 A(2,1) = A(1,0)
120 A(2,0) = A(2,0) + K**4
125 B(0,0) = B(0,0) + LOG(D)
130 B(1,0) = B(1,0) + K*LOG(D)
132 B(2,0) = B(2,0) + (K**2)*LOG(D)
136 PRINT,138,T,K,D1
138 FMT X3,I3,X4,I2,X2,F8.2
140 NEXT J
145 A(0,2) = N
```

(Continued)

```
148 MAT L = INV(A)
152 MAT S = L*B
156 T1 = EXP(S(2,0))
157 T2 = S(0,0)
158 T3 = -(S(1,0)+S(0,0))
159 GOSUB 340
160 FOR J = 1,5
165 PRINT
170 NEXT J
175 PRINT "THE THREE FIT-CONSTANTS ARE:";
176 PRINT "       THE CALCULATED PARAMETERS ARE:"
178 PRINT
180 PRINT,182,S(0,0),T1
182 FMT X4,"B2 = ",F8.5,X22,"A  = ",F8.5
184 PRINT,186,S(1,0),T2
186 FMT X4,"B1 = ",F8.5,X22,"A2 = ",F8.5
188 PRINT,190,S(2,0),T3
190 FMT X4,"B0 = ",F8.5,X22,"A1 = ",F8.5
280 PRINT
282 PRINT
300 M = S + N*(S(2,0)**2) + (S(1,0)**2)*A(0,0)
302 M = M + (S(0,0)**2)*A(2,0) - 2*S(2,0)*B(0,0)
304 M = M - 2*S(1,0)*B(1,0) - 2*S(0,0)*B(2,0)
306 M = M + 2*S(2,0)*S(1,0)*A(0,1)
307 M = M + 2*S(2,0)*S(0,0)*A(0,0)
308 M = M + 2*S(1,0)*S(0,0)*A(1,0)
310 R = SQR(1-(M/(S-(B(0,0)**2)/N)))
315 PRINT,320,R
320 FMT "CORRELATION COEFFICIENT IS ",F8.4
324 FOR J = 1,5
328 PRINT
332 NEXT J
335 GOTO 800
340 PRINT
342 PRINT
344 PRINT,346,C
346 FMT "MEASURED BASE-PLUS-FOG IS ",F8.2
348 RETURN
400 PRINT "INPUT DATA ARE:                    (I = EXPOSURE TIME (MIN))"
401 PRINT,402
402 FMT X28,"(K = NUMBER OF ALUMINUM LAYERS)"
403 PRINT,404
404 FMT X28,"(D = CORRESPONDING TABLET DENSITY)"
405 PRINT,408
408 FMT X5,"I",X5,"K",X8,"D"
409 PRINT
410 RETURN
```

(Continued)

```
750 PRINT,752,TIM(1),TIM(2),TIM(3)
752 FMT "ALUM/X-RAY TABLET CALCULATIONS",X16,I3,"/",I3,"/",I3
753 PRINT "(FOR EXPOSURE OF NBS PHOTOGRAPHIC EDGES)"
754 FOR J = 1,4
755 PRINT
756 NEXT J
758 RETURN
800 PRINT "FOR THESE CONSTANTS, THE EFFECTIVE ALUMINUM"
805 PRINT "STEP-THICKNESS TRANSMITTANCE FACTOR IS:"
806 PRINT
807 PRINT "          K                    T(K)"
808 PRINT
809 FOR J = 0,7
810 Z = EXP(-(T3+T2)*J + T2*(J**2))
820 PRINT,825, J,Z
825 FMT X7,I2,X11,F8.5
828 NEXT J
830 FOR J = 1,6
832 PRINT
834 NEXT J
836 GOSUB 850
838 FOR J = 1,N
840 P(J) = W(J)*EXP(-(T3+T2)*X(J) + T2*(X(J)**2))
842 PRINT,843,Y(J),P(J)
843 FMT X7,F8.2,X7,F8.2
844 NEXT J
845 PRINT
846 PRINT
848 GOTO 862
850 PRINT "THE DENSITY-EXPOSURE POINTS";
851 PRINT "       (D = OPTICAL (DIFFUSE) DENSITY)"
852 PRINT "FOR THE INPUT DATA ARE:";
853 PRINT "            (E = EXPOSURE (INTENSITY-MIN))"
854 PRINT
855 PRINT
856 PRINT,857
857 FMT X13,"D",X13,"E"
858 PRINT
860 RETURN
862 S1 = 0
863 S2 = 0
864 S3 = 0
865 S4 = 0
866 S5 = 0
```

(Continued)

```
868 FØR J = 1,N
869 S1 = S1 + Y(J)
870 S2 = S2 + P(J)
871 S3 = S3 + Y(J)*P(J)
872 S4 = S4 + (Y(J)**2)
873 S5 = S5 + (P(J)**2)
875 NEXT J
878 S6 = S1/N
879 S7 = S2/N
880 S8 = SQR((S5/N)-(S7)**2)
881 S9 = SQR((S4/N)-(S6)**2)
882 R2 = ((S3/N)-S6*S7)/(S8*S9)
884 R4 = S9*SQR(1-(R2)**2)
886 PRINT,890,3*R4
890 FMT "3-SIGMA IN DENSITY IS ",F8.3
891 FØR J = 1,5
892 PRINT
893 NEXT J
895 GØTØ 999
900 DATA 32,0.04
905 DATA 20,7,0.34,20,6,0.38,20,5,0.44,20,4,0.53,20,3,0.65
907 DATA 20,2,0.87,20,1,1.25,20,0,1.81
909 DATA 15,7,0.26,15,6,0.29,15,5,0.33,15,4,0.40
911 DATA 15,3,0.51,15,2,0.67,15,1,0.96,15,0,1.42
913 DATA 15,7,0.26,15,6,0.29,15,5,0.34,15,4,0.42
915 DATA 15,3,0.52,15,2,0.68,15,1,0.95,15,0,1.41
917 DATA 20,7,0.32,20,6,0.35,20,5,0.41,20,4,0.50
919 DATA 20,3,0.64,20,2,0.86,20,1,1.20,20,0,1.78
999 END
```

Typical Output Listing for DOODAH (on next three pages)

```
?BASIC DØØDAH
RUN


ALUM/X-RAY TABLET CALCULATIØNS                          7/ 15/ 76
(FØR EXPØSURE ØF NBS PHØTØGRAPHIC EDGES)


INPUT DATA ARE:                    (T = EXPØSURE TIME (MIN))
                                   (K = NUMBER ØF ALUMINUM LAYERS)
                                   (D = CØRRESPØNDING TABLET DENSITY)
     T       K          D

    20       7         .34
    20       6         .38
    20       5         .44
    20       4         .53
    20       3         .65
    20       2         .87
    20       1        1.25
    20       0        1.81
    15       7         .26
    15       6         .29
    15       5         .33
    15       4         .40
    15       3         .51
    15       2         .67
    15       1         .96
    15       0        1.42
    15       7         .26
    15       6         .29
    15       5         .34
    15       4         .42
    15       3         .52
    15       2         .68
    15       1         .95
    15       0        1.41
    20       7         .32
    20       6         .35
    20       5         .41
    20       4         .50
    20       3         .64
    20       2         .86
    20       1        1.20
    20       0        1.78

MEASURED BASE-PLUS-FØG IS       .04
```

(Continued)

THE THREE FIT-CØNSTANTS ARE:

B2 = .02342
B1 = -.42271
B0 = -2.41422

THE CALCULATED PARAMETERS ARE:

A = .08944
A2 = .02342
A1 = .39929

CØRRELATIØN CØEFFICIENT IS .9989

FØR THESE CØNSTANTS, THE EFFECTIVE ALUMINUM STEP-THICKNESS TRANSMITTANCE FACTØR IS:

K	T(K)
0	1.00000
1	.67080
2	.47154
3	.34737
4	.26816
5	.21695
6	.18392
7	.16341

(Continued)

THE DENSITY-EXPOSURE POINTS FOR THE INPUT DATA ARE:

(D = OPTICAL (DIFFUSE) DENSITY)
(E = EXPOSURE (INTENSITY-MIN))

D	E
.34	3.27
.38	3.68
.44	4.34
.53	5.36
.65	6.95
.87	9.43
1.25	13.42
1.81	20.00
.26	2.45
.29	2.76
.33	3.25
.40	4.02
.51	5.21
.67	7.07
.96	10.06
1.42	15.00
.26	2.45
.29	2.76
.34	3.25
.42	4.02
.52	5.21
.68	7.07
.95	10.06
1.41	15.00
.32	3.27
.35	3.68
.41	4.34
.50	5.36
.64	6.95
.86	9.43
1.20	13.42
1.78	20.00

3-SIGMA IN DENSITY IS .054

999 EXIT

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The history of edge-objects for use in optical and photographic testing is briefly reviewed and culminates in a short summary of the techniques developed at NBS in 1965 for producing photographic edges by x-ray exposures of High Resolution Plates with a tantalum strip to generate the discontinuity. The report then covers the development of an improved method for producing these edge-artifacts. It is shown that with x-ray exposure, the relation of density to exposure is linear up to densities of approximately 2.0. This linear relation is then exploited to produce two kinds of edge-artifacts. Both artifacts contain ten (10) values of density and three edge-discontinuities. The edges on one artifact have the same value of contrast, with different mean densities, while the edges on the other have different values of contrast. The use of each type is discussed. Techniques for determining exposures, for determining the transmittances of the aluminum step tablets used to modulate x-ray exposure and for determining the linear relation between density and exposure are presented in mathematical detail and exemplified in subsequent illustrative experiments. Some inherent limitations of the method are discussed. It is concluded that there is sufficient flexibility to the process and procedures to provide sharp edges, in a wide range of contrasts, on demand.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)

Densitometry; Edge objects; Microdensitometry; Photographic edges; Photographic process

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